Variations in the Teleconnection of ENSO and Summer Rainfall in Northern China: A Role of the Indian Summer Monsoon*

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Variations in the Teleconnection of ENSO and Summer Rainfall in Northern China: A Role of the Indian Summer Monsoon*

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ABSTRACT

Observational studies have created a dilemma on how El Niño–Southern Oscillation (ENSO) may have affected interannual variations of summer rainfall in northern China; some suggested a consistent effect while others showed a complete lack of effect. This dilemma is resolved in this study, which shows that ENSO has affected the summer rainfall in northern China and the effect has varied at multidecadal scales. The question of how the ENSO teleconnection with northern China rainfall variation was established is addressed, and an answer pointing to the Indian summer monsoon as a ''facilitator'' connecting ENSO and northern China rainfall variation is examined. The Indian monsoon circulation interacted with the regional circulations in northern China in some epochs and such interaction was interrupted in other epochs. When the interaction was active, the Indian monsoon variations originating from ENSO, during El Niño or La Niña, was extended to affect the rainfall variation in northern China, creating a teleconnection of ENSO with northern China rainfall. When the interaction weakened or was inactive, the ENSO effect languished. Additional analyses were done to address the related question of why the interactions have alternated. The alternation was suggested to result from variations of the large-scale circulation in the Eurasian continent. The circulation anomalies showed lowering (rising) 500-hPa geopotential height centered at Mongolia and western China in some epochs, enhancing cyclonic (anticyclonic) rotation in mid- and low-level winds and creating (disrupting) a moisture convoy from the Indian monsoon region to northern China and synergetic convergence/divergence anomalies in the monsoon region and in northern China. Results of this study contribute to the understanding of interannual and multidecadal variations of the summer rainfall in the semiarid region of northern China.

1. Introduction

In the last three decades of the twentieth century, frequent and intense droughts in northern China (37.5°–42.5°N, 107°–120°E; see Fig. 1a) caused ''routine'' interruptions to the flow of the Yellow River in spring and early summer months, damaging the region's ecosystems and environment (Hu and Feng 2001; Qian and Zhu 2001). In response to the repeated severe droughts, great effort has been devoted to understanding the region's precipitation variation with the goal to improve predictions of spring and summer rainfall at interannual and decadal time scales and to increase use of the predictions in water resources planning and management (Ding 2003). Many studies examined the influence of El Niño–South Oscillation (ENSO) on interannual variations of the summer rainfall in northern China (Huang and Wu 1989; Ding 1994; Zhang et al. 1999). These studies found that when El Niño was in the developing and maturing stage, northern China often endured summer rainfall shortage. Rain became abundant when the warming in an El Niño event faded. These results suggested an ENSO effect on the summer rainfall in northern China. A related question is how this ENSO teleconnection was established.

One speculated process of this teleconnection is that the decrease of the sea surface temperature (SST) in the western tropical Pacific during El Niño years suppresses atmospheric convection in the region. The subsequently developed high pressure anomaly in the region and associated adjustment of the mass field initiated a wave train in the pressure field emanating to the higher latitudes and affecting the circulation and summer rainfall in eastern and northern China, the Korean peninsula, and Japan. This anomaly pattern in the pressure field related to ENSO is shown in Fig. 1b, and has been referred to as the Pacific–Japan (PJ) teleconnection (Nitta 1987). This PJ pattern has strongly affected the summer rainfall in the Yangtze and Huai River valley in southeastern China and Japan (Fig. 1c), but has a rather

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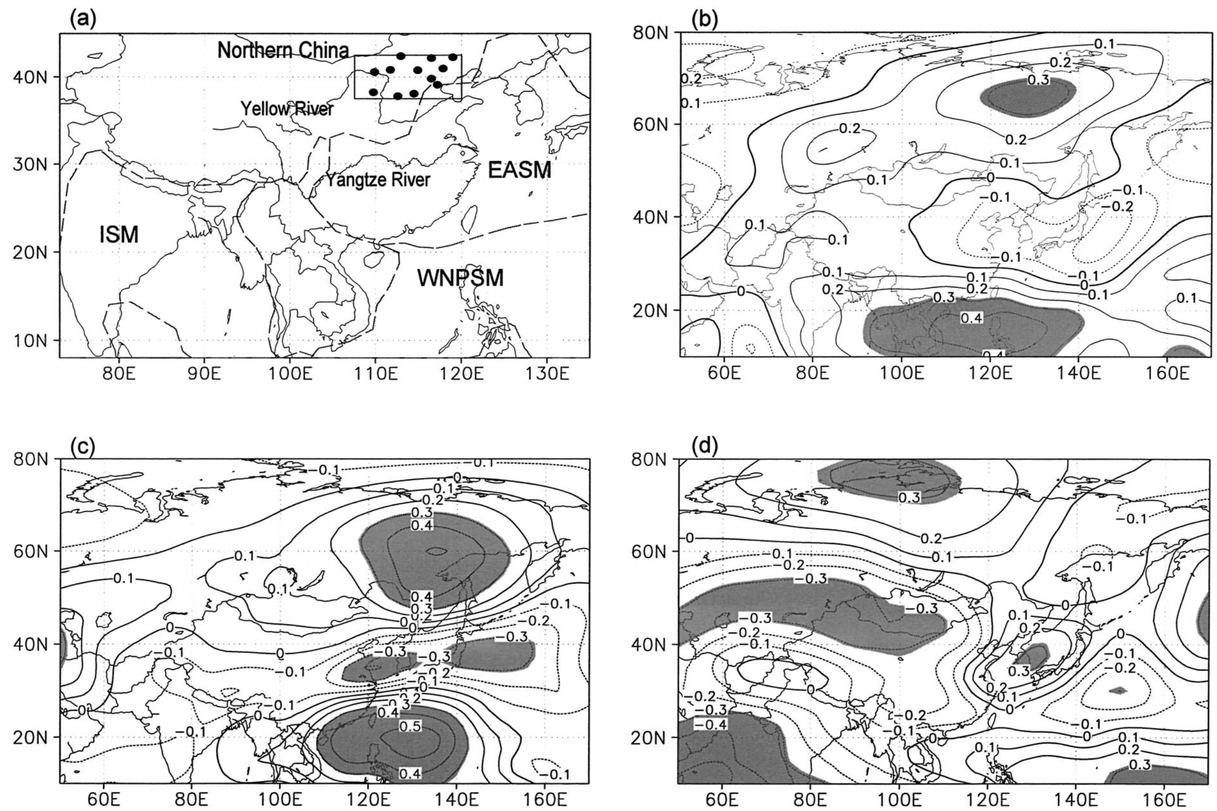

FIG. 1. (a) The rectangular box in the map is ''northern China'' referred to in this study. The stations used to calculate the area-average summer rainfall (dots). The boundaries of different monsoon systems (dashed lines) (after Wang and LinHo 2002). (b) The correlation between northern winter Niño-3.4 SST anomaly and northern summer 500-hPa geopotential height, showing the PJ teleconnection pattern. (c) Correlation between summer rainfall in Yangtze and Hui River valley, 27.5°–25.0°N, 115.0°–122.5°E, and 500-hPa geopotential height. (d) Correlation between the summer rainfall in northern China and the 500-hPa geopotential height. Zonal average was removed before correlations are calculated. (b), (c), (d) Shading indicates 95% confidence level of correlation.

weak effect on rainfall in northern China (Huang 2004). In fact, the correlation of summer rainfall in northern China versus the 500-hPa pressure anomaly showed a pattern (Fig. 1d) utterly different from the PJ pattern, indicating that the processes connecting ENSO with rainfall variations in northern China differ from the PJ teleconnection. From a different perspective, the PJ teleconnection has been found closely related to the variations of the East Asian summer monsoon (Huang et al. 2003; Huang 2004). Because northern China is located north of the East Asian summer monsoon region (Fig. 1a; also see Fig. 9 in Wang and LinHo 2002) the PJ pattern would have little effect on the northern China summer rainfall.

Another process that could extend the ENSO effect onto the summer rainfall variation in northern China is the Indian summer monsoon. The Indian summer monsoon rainfall anomaly has been found to affect the summer rainfall in northern China (Guo and Wang 1988; Yatagai and Yasunari 1995). Because the monsoon was often influenced by ENSO activity (Lau and Nath 2000, 2003; Lau et al. 2000; Shukla and Paolino 1983; Krishnamurthy and Goswami 2000), it is reasonable to consider that northern China summer rainfall variation could have been related to ENSO by its effect on the Indian summer monsoon circulation. Some evidence supporting this notion was provided in Zhang et al. (1999), who showed that the northward flux of atmospheric moisture originating from the Indian monsoon region was significantly correlated with moisture convergence and summer rainfall in northern China. Specifically, weak (strong) Indian summer monsoon corresponded to weak (strong) water vapor fluxes and deficient (excessive) summer rainfall in northern China.

This plausible relationship between ENSO, the Indian summer monsoon, and northern China summer rainfall variations was not supported in Wang (1994) however, who showed no relationship between ENSO and the summer rainfall in northern China. This discrepancy among results of these studies could have arisen from the fact that Wang examined the average relationship using nearly 100 yr of data in the twentieth century whereas Zhang only used data after 1951. Their different outcomes from using data of different record lengths could have suggested a temporally varying relationship between ENSO and the summer rainfall in northern China. Such a varying relationship may have been ''averaged out'' in Wang's result.

In this study, we examine the relationship and its dynamic aspects between ENSO and the summer rainfall in northern China, focusing on the role of the Indian summer monsoon in facilitating the ENSO teleconnection with northern China summer rainfall. Specific questions to be answered are 1) what was the relationship between variations of the summer rainfall in northern China and the Indian summer monsoon rainfall, 2) if and how has this relationship varied, and 3) what role has this relationship played in facilitating the ENSO effect on variations of the summer rainfall in northern China? While answering these questions, we will reveal the dynamic features of the teleconnection of ENSO with summer rainfall in northern China, and show how these features may be used to improve the northern China summer rainfall prediction at interannual and decadal scales.

2. Data

Data used in this study are monthly precipitation in northern China and monthly all-India rainfall, global SST, and atmospheric moisture and wind fields. Monthly precipitation data for China were obtained from Dai et al. (1997). The data are in a gridded format of 2.5° latitude × 2.5° longitude resolution from 1851–1995. Rainfall data from individual stations in northern China also were used to extend the Dai et al. data to 1998. From this extended rainfall dataset, we calculated the summer rainfall in northern China as the total rainfall of June–July–August (JJA), averaged in the areas 37.5°–42.5°N and 107°–120°E.

Monthly all-India rainfall data for the period 1871–1998 were obtained from the Indian Institute of Tropical Meteorology (Parthasarathy et al. 1995). From the monthly data, we calculated the all-India JJA rainfall. Unlike some studies which counted the September rainfall in the Indian summer monsoon, we excluded the September rainfall in this study for the reason that the effect of the Indian summer monsoon on the rainfall in northern China weakened considerably or disappeared starting in September following the southward retreat of the monsoon front (e.g., the ''mei-yu front'' in China). Rainfall in September in northern China often results from polar frontal processes (Zhang and Ge 1983). Another reason is that September usually has the largest response in monthly Indian rainfall variation to ENSO anomalies (Slingo 1999), mainly because of amplifying SST anomalies in ENSO events toward the end of a calendar year, that is, the ENSO ''phase-lock'' with the annual cycle. When September rainfall was included in the Indian summer rainfall, its variation would have a large contribution from those anomalies occurring primarily in September. Because those anomalies have no effect on JJA rainfall variation in northern China, we excluded the September rainfall in the calculation of the all-India summer monsoon rainfall.

In this study, ENSO was described by the Niño-3.4 (5°N–5°S, 120°–170°W) SST variation calculated using the SST data from the United Kingdom Met Office Hadley Center Global Sea Ice and Sea Surface Temperature Dataset (HadISST1; Rayner et al. 2003). It covers the period 1871–1998 with a spatial resolution is 1.0° latitude × 1.0° longitude. Improved data properties and accuracy of the HadISSTl dataset, compared to its predecessor GISST, include better resolution of local variation signals and more uniform variance in time of data variation, warranting the use of the dataset in this analysis.

The National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data for 1948–98 (Kalnay et al. 1996) were used to analyze atmospheric circulations in those 50 yr. There have been many concerns regarding the quality of the reanalysis data and potential artifacts in the data that might have contributed to false decadal-scale variations of some variables. Indeed, weather observation systems, including surface and radiosonde sensors and observation schedule/frequency and methods were upgraded and changed over the last five decades. Each of those changes influenced the observation data, resulting in certain biases in the data to various degrees of magnitude. Most of the influences have, however, been evaluated and minimized to the best possible extent through quality control and assimilation schemes designed and used to develop the reanalysis dataset (Kalnay et al. 1996). As further shown in Kistler et al. (2001), the data quality in the reanalysis dataset is ''fairly uniform'' from 1950s to the present, and this consistent quality in the (Northern Hemisphere) reanalysis data has resulted from two key features of the reanalysis system: 1) ''with a modern four-dimensional data assimilation system [in the reanalysis] even the early upper-air observing system can produce fairly skillful initial conditions in the Northern Hemisphere,'' and 2) the system is skillful in producing week-long forecasts which were further used to develop, and hence warranted the quality of, the reanalysis data.

Another source of potential bias is the use of satellite observations since 1979 in developing the reanalysis data. The effects of including satellite observations on the data's consistency were examined in Kistler et al. (2001), who showed the same data consistency with and without use of the satellite observation after 1979, thus demonstrating no persistent biases produced in the Northern Hemisphere data after 1979 from using the satellite observations.

Even though major biases were eliminated in the reanalysis dataset, the addition of different data sources and upgrading existing observation systems have had some effect on the reanalysis data. For example, when using the data in analyses of Asian monsoons, Quan et al. (2003) found that changes in observation systems and the addition of satellite data have affected amplitudes of decadal- and multidecadal-scale variations in the monsoons. These biases are deemed minor, however, because they caused little change in the presence, frequency, and spatial pattern of variations at those scales. Quan et al. found that the trends and spatial patterns of multidecadal variations in precipitation derived from the reanalysis data were consistent with the results from using local stations' observations. A similar conclusion also was reached by Chelliah (1999) for wind and temperature data.

With these quality data, we examine northern China summer rainfall variation and its relationship with the Indian summer monsoon and ENSO. Methods used in the analyses are described in the text.

3. Indian summer monsoon as a link between the rainfall variation in northern China and ENSO

Previous studies (e.g., Shukla and Paolino 1983; Kumar et al. 1999) showed that in the warm phase of the ENSO cycle (El Niño), surface pressure increased and atmospheric convection was suppressed in the western equatorial Pacific Ocean and the Indian Ocean. These anomalies often persisted for a couple of years following the El Niño development and affected the Indian summer monsoon. For example, the southwesterly monsoon wind weakened, and the lack of this monsoon wind caused a large deficit in Indian summer rainfall. This anomaly pattern reversed during La Niña.

This Indian summer monsoon–ENSO relationship has been varying (e.g., Kinter et al. 2002; Kumar et al. 1999; Torrence and Webster 1999; Wang et al. 2001). The variation of this relationship is shown in Fig. 2a; a statistically significant negative correlation occurred from 1880 to 1915, except for a short break around 1888. The relationship weakened dramatically after 1915, and the weak relationship persisted from 1916 to 1930. Another cycle of strong to weak relationship was completed from 1932 to 1958, and the relationship was reinforced from 1960 through the mid-1980s, before weakening again after the mid-1980s.

Because the Indian monsoon variation has been found to affect variations of the summer (JJA) rainfall in northern China, we speculate that through this Indian summer monsoon–ENSO relationship the Indian monsoon may have extended the ENSO effect onto the northern China rainfall variation. Before examining the role of the Indian monsoon, we present in Fig. 2b a statistical finding showing that ENSO has indeed influenced the northern China summer rainfall. Moreover, this influence has also varied. An intriguing aspect of this variation is that it is different from that in Fig. 2a, a fact indicating that the Indian monsoon was not simply relaying its influence from ENSO to northern China summer rainfall. The major differences between Figs. 2b and 2a are 1) the ENSO and Indian summer rainfall (Fig. 2a) had a strong correlation from 1905 to 1915 whereas the ENSO relationship with northern China rainfall was insignificant (Fig. 2b); 2) a marginally significant correlation between ENSO and northern China rainfall persisted from 1926 to 1940 when ENSO and Indian summer rainfall had a fairly strong correlation; and 3) the transition from strong to weak correlation in Fig. 2b often occurred when the Indian summer monsoon–ENSO correlation was still strong. Clearly, the processes connecting ENSO with northern China summer rainfall are quite different from those associating ENSO and the Indian summer monsoon rainfall variation. A subsequent question is what are the processes connecting ENSO with the northern China summer rainfall, and specifically, if the Indian monsoon may have played a role in establishing such a connection through interactions with the northern China summer rainfall? We now examine this role of the Indian monsoon and address this question.

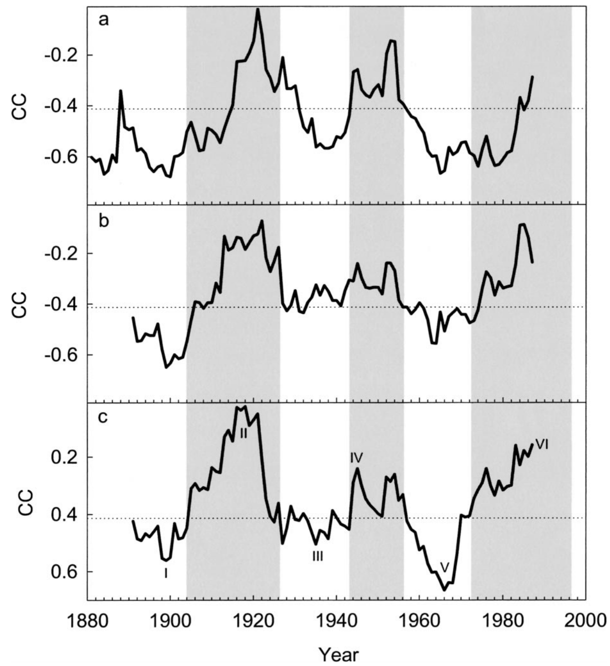

FIG. 2. Variation of 21-yr moving correlation of (a) all-India JJA rainfall vs the Niño-3.4 SST, (b) northern China JJA rainfall vs the Niño-3.4 SST, and (c) northern China JJA rainfall vs all-India JJA rainfall. (a)–(c) The 95% confidence level for correlation (dotted line). To facilitate comparison, the correlation coefficients in (c) were plotted from large to small in the coordinate. [(c) The changes between the epochs, for example, I vs II, II vs III, . . . , V vs VI were tested for their significance using Fisher's Z-transform (Wilks 1995). The result indicated the changes are significant at 90% and higher confidence levels except for the difference between epoch III and IV, when III was marginally significant (see text for interpretations).]

We start by showing in Fig. 2c the correlation between northern China summer rainfall and the Indian summer monsoon variations. To facilitate the discussion, their correlation coefficients were plotted from large to small in the coordinate of Fig. 2c. Compared to the variations in Figs. 2a and 2b, Fig. 2c depicts a variation very similar to that in Fig. 2b. Most noticeably, the changes or the major transitions of the relationship in Fig. 2c coincide with the changes of the ENSO relation with the northern China summer rainfall, and the strong (weak) ENSO effect on northern China rainfall persisted almost at the exact time when the correlation between northern China rainfall and the Indian summer monsoon was significant (insignificant). For example, in the epochs 1904–26, 1943–57, and the recent one after 1972, the correlation between northern China rainfall and the Indian monsoon was weak and so was the correlation of ENSO and the northern China rainfall. Similarly consistent but strong correlations were shown in other epochs of 1890–1904 and 1957–72. According to these consistent variations, when ENSO was influencing the Indian summer monsoon variation, the ENSO also could affect northern China summer rainfall if the rainfall is affected by the Indian summer monsoon variation. This connection is observed in the epochs of 1890–1904 and 1957–72. If this connection weakened or broke, the ENSO effect would be absent in northern China summer rainfall variation even if ENSO has a strong effect on the Indian monsoon, such as in the epoch of 1943–57 and the recent epoch after 1972. These cohesive variations between the correlation of northern China rainfall versus the Indian monsoon and the correlation of the northern China rainfall versus ENSO suggest a role of the Indian summer monsoon in connecting ENSO effects with the northern China rainfall variation.

This speculation is further supported by results from comparisons of the variations shown in Figs. 2b and 2c with the variations in the correlation between the Indian monsoon and ENSO in Fig. 2a. Focusing on the shaded epochs in Figs. 2a–c, we can find that, although the ENSO effect on the Indian monsoon rainfall was strong from 1880 to 1915 (Fig. 2a) the ENSO correlation with northern China rainfall weakened in 1905 (Fig. 2b), starting much earlier than 1915, following a weakening in the relationship between the northern China rainfall and the Indian monsoon (Fig. 2c). Before 1905, the ENSO effect on northern China rainfall was strong (Fig. 2b) when both the ENSO effect on the Indian monsoon and the monsoon's effect on northern China rainfall were strong (Figs. 2a and 2c). [In the epoch 1927–43, the ENSO effect on northern China rainfall was marginally significant (at 95% confidence level) because its relationship with the Indian monsoon was marginally significant even though the ENSO effect on the Indian monsoon remained very strong in most years of that epoch.] Finally, in recent decades after 1970, when the relationship between the Indian monsoon and northern China rainfall weakened around 1972 the ENSO effect on northern China rainfall weakened simultaneously, even though the ENSO effect on the Indian summer monsoon remained strong for another one and a half decades before weakening (similar to the case in the early decades of the twentieth century). These details elucidate a role of the Indian summer monsoon in carrying on the ENSO influence to affect the summer rainfall variation in northern China.

The significance of this role of the Indian monsoon is further evidenced by results from the following analyses. First, because other monsoon processes, such as the East Asia summer monsoon (EASM) and western North Pacific summer monsoon (WNPSM; see Fig. 1a), also could have affected northern China rainfall and extended the ENSO effect on it (Wang and LinHo 2002), we compared such effects and found that these other monsoons have much less influence on northern China summer rainfall than the Indian monsoon does and, hence, carry little ENSO effect to the China rainfall variation. Again, this result could arise because northern China is out of the EASM and WNPSM domain (Fig. 1a). Second, since ENSO intensity peaks during the boreal winter months and could have initiated circulation anomalies that *lead* to anomalies of northern China rainfall in the following summer, we examined this possibility. The results show that the peak SST anomalies in the boreal winter months during El Niño events have had little influence on northern China summer rainfall variation and, thus, assure the Indian summer monsoon's role in connecting the ENSO with northern China rainfall. Details of these results are summarized in Fig. 3.

Figures 3a–f show the correlations of the JJA northern China rainfall (thin line) and JJA all-India rainfall (thick line) with Niño-3.4 SST variations in the six different epochs (I–VI in Fig. 2c). Figures 3a,c,e are for the epochs with *significant* correlations between the Indian summer monsoon and the rainfall in northern China, and Figs. 3b,d,f are for the epochs with *insignificant* correlations between the two rainfall variations. A striking feature in Figs. 3a,c,e is that there is no leading effect of antecedent winter SST anomaly associated with ENSO on either the northern China summer rainfall or the Indian summer monsoon rainfall. The simultaneous negative correlation is most significant in June, July, and August in those three epochs. These results indicate that the antecedent winter SST anomalies during El Niño do not lead to JJA rainfall anomalies in the Indian peninsula nor in northern China; it was the JJA SST anomalies that have had the most effect on the JJA rainfall in those two regions. An important implication of these results emerges from their comparisons with the results in Fig. 11 in Wang et al. (2001), who showed correlations between the WNPSM and the Niño-3.4 SST. The WNPSM index has a significant lagged correlation with the Niño-3.4 SST, a result quite different from those in Figs. 3a,c,e. This difference indicates that the northern China summer rainfall variation is not affected to any significant extent by the WNPSM nor by the EASM, which is closely related with the former monsoon system (Ye and Huang 1996; Wang et al. 2001; Wang and LinHo 2002). Should the northern China rainfall have been influenced by the WNPSM and EASM, the rainfall variations in Figs. 3a,c,e would have had a similar persistent (time invariant) lagged correlation with the SST

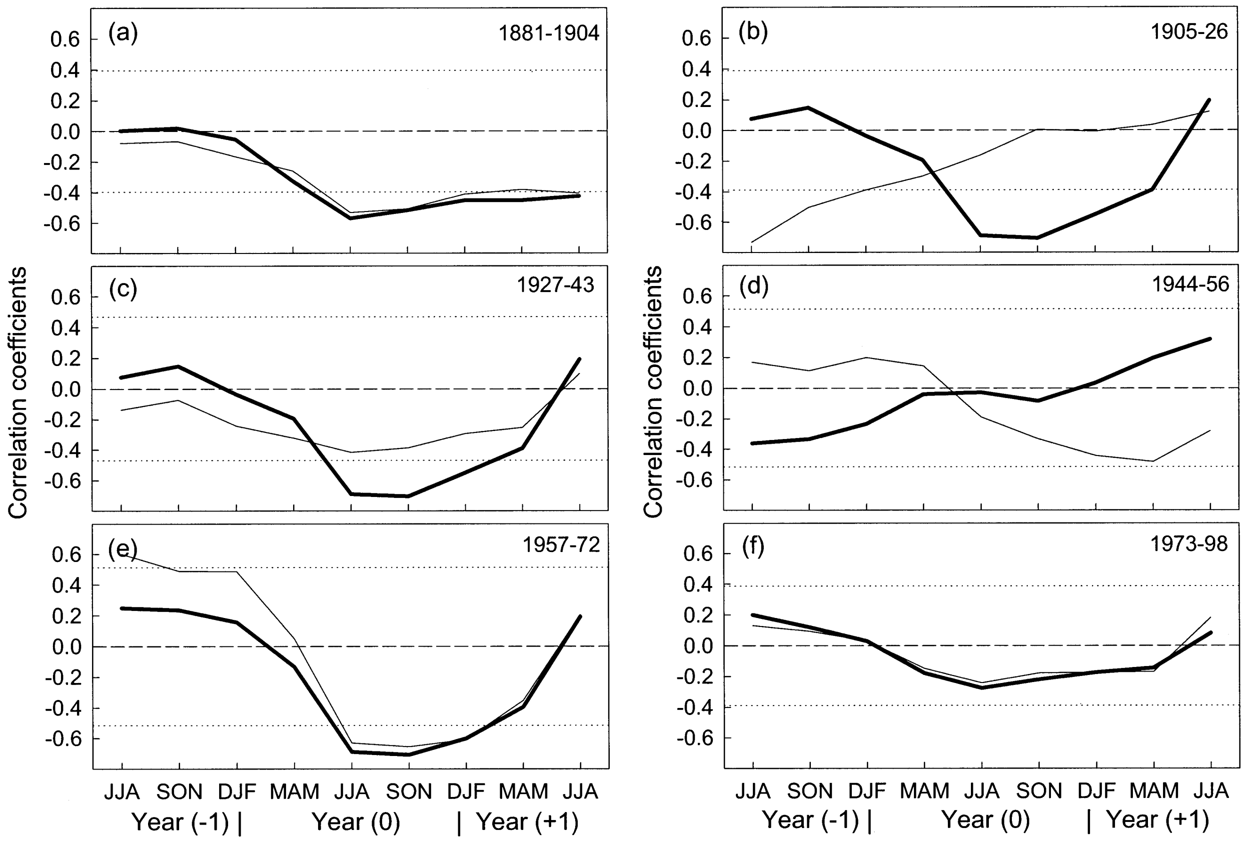

FIG. 3. Lagged correlations of seasonal Niño-3.4 SST anomalies vs the JJA all-India (thick line) and northern China precipitation anomalies (thin line) for the epochs of (a) 1881–1904, (b) 1905–26, (c) 1927–43, (d) 1944–56, (e) 1957–72, and (f) 1973–98. The dotted horizontal lines indicate 95% confident level. Year (−1), (0), and (+1) indicate correlations of the regions' rainfall with seasonal Niño-3.4 SST of previous, current, and following year, respectively.

variations whenever an El Niño/La Niña occurred. These differences further illuminate the role of the Indian summer monsoon in northern China rainfall variation and in connecting them with ENSO in those specific epochs.

This unique role of the Indian monsoon also is supported by the consistent correlations in Figs. 3a,c,e between northern China rainfall and the Niño-3.4 SST and between the Indian monsoon and the same SST. Such persistent and nearly identical correlations in three distant epochs could have only occurred when summer rainfall variations in the Indian monsoon region and northern China are closely related, thus reiterating the connection of variations in the Indian monsoon rainfall and northern China summer rainfall.

In the epochs when the Indian summer monsoon and northern China summer rainfall have insignificant correlation (Figs. 3b,d,f), the relationship of northern China summer rainfall with the Niño-3.4 SST becomes disorganized. For instance, in the epoch 1943–56 and the most recent epoch the rainfall variations in northern China were not significantly related to the ENSO variation. It happened in those epochs that the Indian summer monsoon was not significantly correlated with ENSO either. Another interesting case is in the epoch 1904–26 (Fig. 3b) when ENSO significantly affected the Indian monsoon rainfall but had little effect on northern China JJA rainfall (Figs. 2a and 2b) because of the lack of a connection between the summer rainfall variations in northern China and in India (Fig. 2c).

These results show from various perspectives that the summer rainfall variation in northern China has been closely related to variations of the Indian summer monsoon in some epochs and, through this connection, the Indian monsoon has extended the ENSO effects to the northern China rainfall variation.

4. Why has the relationship between variations in northern China summer rainfall and the Indian monsoon varied?

As shown in Fig. 2, the variation in the relationship between northern China summer rainfall and the Indian summer monsoon rainfall is different from that between the Indian monsoon and ENSO. This difference indicates that processes affecting the former relationship are different from those influencing the latter. Since the former has been playing a key role in connecting ENSO with northern China summer rainfall changes, we examine processes that could have contributed to the variation of that relationship so that the understanding may be used to improve prediction of summer rainfall variation in northern China. Given the ''teleconnection'' nature of the northern China rainfall and the Indian summer monsoon variations, their relationship and its alternation could only be attributed to the large-scale circulations over the Eurasian continent. Thereby, different circulations and associated dynamic configurations are expected in the different epochs. To uncover these differences and identify dynamic features of the circulation we used the NCEP–NCAR reanalysis data and calculated the low-level atmospheric moisture flux and convergence/divergence for the recent two opposing epochs: 1957–72 and 1973–98. Figure 4a shows the moisture flux integrated between sigma levels 19–28 (equivalent to from surface to 700 hPa) averaged in 1957–72, and Fig. 4b shows moisture flux averaged for epoch 1973–98. Their differences, shown in Fig. 4c, depict a clear contrast of moisture flux in northern China between the different epochs: In 1957–72, the circulation featured an atmospheric moisture convoy from the Indian monsoon region to northern China across the central eastern portion of China. This convoy helped connect the moisture variation in the Indian monsoon with that in northern China. This convoy was absent however in the epoch 1973–98, and the moisture variation in northern China was disconnected from and not considerably affected by the Indian monsoon variation.

In association with the moisture convoy, the dynamics of the large-scale circulation created convergence anomalies featuring cohesive variations of moisture convergence in northern China and the Indian monsoon region. For instance, in epoch 1957–72, there were two distinct anomaly centers of moisture convergence/divergence along the moisture convoy, one in the northern Arabian Sea and western India and the other in northern China (Fig. 5). These two ''activity centers'' had simultaneously enhanced convergence (Fig. 5a) or divergence (Fig. 5b). In years with moisture convergence anomalies, both the Indian monsoon region and northern China experienced abundant atmospheric moisture and frequent and intense rainfall. In years with moisture divergence anomalies, both regions had drier conditions with less frequent and less intense rainfall. These coherent variations (in both wet and dry years of the epoch) possessed by the large-scale circulation in the epoch also are clearly shown in Fig. 6, which depicts a regression relationship of JJA all-India rainfall and precipitable water of surrounding regions. In 1957–72 (Fig. 6a), northern China was the most positively responsive region to rainfall variations in the Indian monsoon region. These circulation and dynamic properties in the epoch explain the relationship and connection of summer rainfall variations in the two regions. These characteristics were absent in the opposite epoch 1973–98 (Fig. 7), when the moisture convoy was missing in the

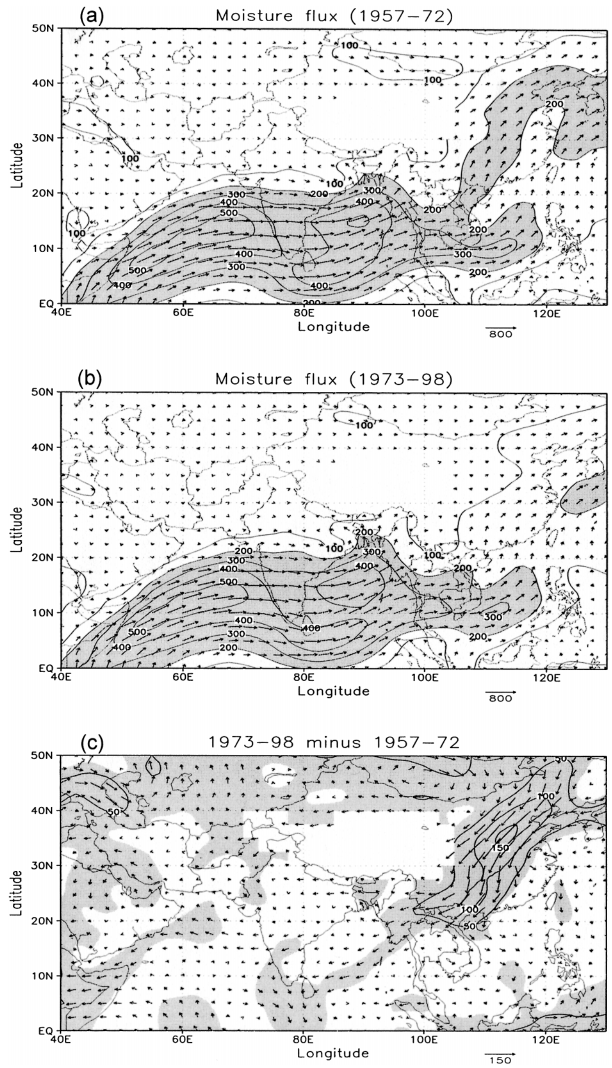

FIG. 4. Moisture flux integrated from surface to 700 hPa for (a) epoch 1957–72, (b) epoch 1973–98, and (c) their differences. The contour lines show flux values with contour interval (a), (b) 100 and (c) 50 kg m^{-1} s^{-1}. The void area is Tibetan Plateau whose elevation is at or above 700 hPa height, and (a), (b) shading indicates moisture flux larger than 200 kg m^{-1} s^{-1}, and (c) shading indicates the changes in moisture flux between (a) and (b) are significant at 95% confident level.

circulation (Fig. 4b) and its dynamics produced less organized moisture convergence/divergence variations in the Indian monsoon region and in northern China (Figs. 7a and 7b). This interruption of the connection also is shown in the precipitatable water variation in Fig. 6b. In such a circulation environment, the rainfall variations in the Indian monsoon region and northern China disengaged (Fig. 2c).

These specific features in the moisture convoy and divergence describe the dynamic aspects of the large-scale circulation and its changes in different epochs and partially explain the alternating relationship between the Indian monsoon and northern China summer rainfall.

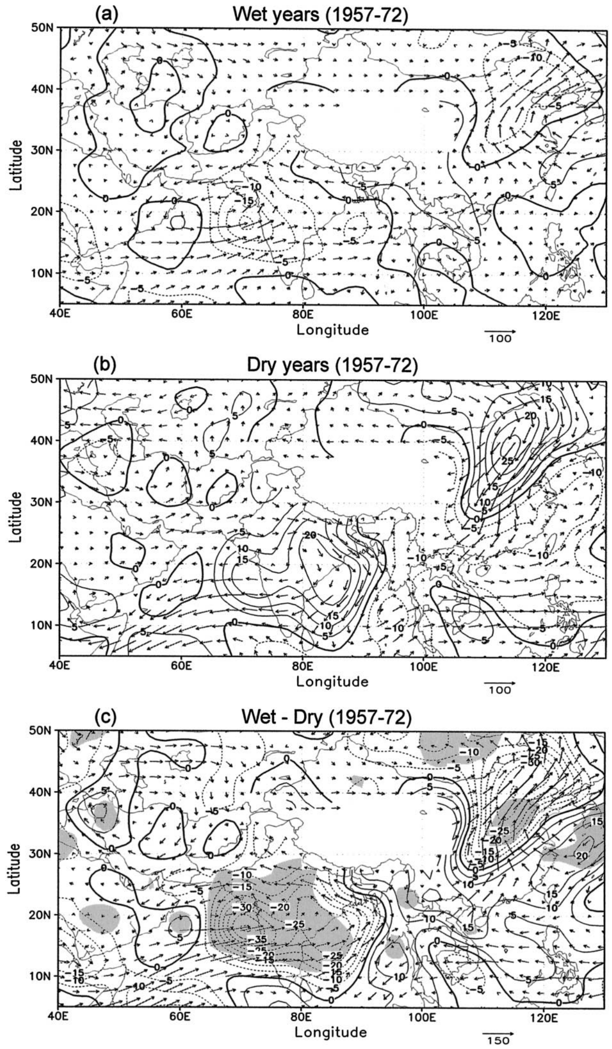

FIG. 5. Composites of vertically integrated moisture flux anomalies (vector) and moisture divergence anomalies (contour) for (a) wet years, (b) dry years, and (c) their difference in epoch 1957–72. Contour interval for moisture divergence is 5.0×10^{-6} kg m^{-2} s^{-1}, and (c) shading indicates difference of moisture divergence anomalies between (a) and (b) is significant at 95% confident level.

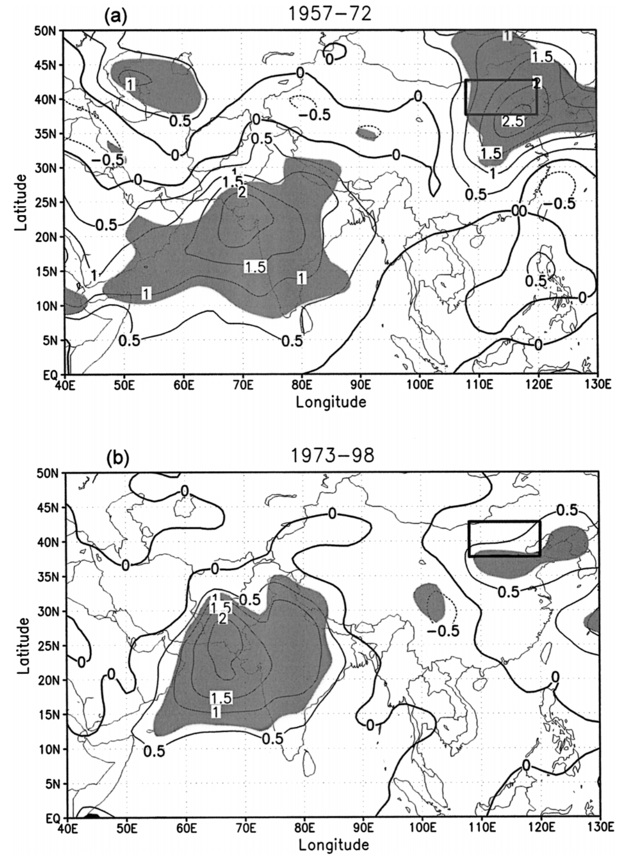

FIG. 6. Anomaly of integrated troposphere precipitable water in response to unit standard deviation of Indian summer monsoon rainfall in (a) epoch 1957–72 and (b) epoch 1973–98 (unit: mm). Shading indicates significant responses at 95% confidence level. (The rectangular box depicts the study area.)

These features and related dynamic processes develop from the unique circulation anomalies in those epochs. These anomalies are shown in Fig. 8a by the 500-hPa geopotential height anomalies. In the epoch 1957–72, the circulation shows a lowering of the 500-hPa geopotential height in a broad region across the Eurasian continent and from the equator to the polar region. A center of the negative geopotential height anomalies is in Mongolia and northwestern China stretching further west to Kazakhstan. Positive height anomalies are in the western North Pacific and northern Europe. This anomaly pattern of geopotential height indicates an associated anomaly of cyclonic rotation in mid- and low-level winds. Consequently, the flows along the south and east flank of the Asian continent are enhanced, supporting the development of the moisture convoy from the Indian monsoon region to northern China (Fig. 4a) and the cohesive variation in moisture convergence and rising atmospheric precipitable water in those two regions (Figs. 5a and 6a). Thus, their rainfall variations ''engaged'' and showed the strong correlations (Fig. 2c). In the same epoch, variations in the Indian summer monsoon resulting from ENSO could affect summer rainfall variation in northern China. Hence, the Indian monsoon has played an active role in this epoch to extend the ENSO influence on the northern China rainfall variation.

In the recent epoch 1973–98, a near mirror image of Fig. 8a with reversed signs in anomalies describes the circulation anomaly (a near mirror image resulted because the anomalies were relative to the average over the period 1957–98). This pattern of circulation anomaly indicates a rise of the geopotential height across most of the Eurasian continent and centered in northern China and Mongolia. The rising pressure and enhanced anticyclonic rotation in winds, especially across southern and eastern China, disrupted the moisture convoy from the Indian monsoon region to northern China. Moreover, the increasing anticyclonic rotation changed the dynam-

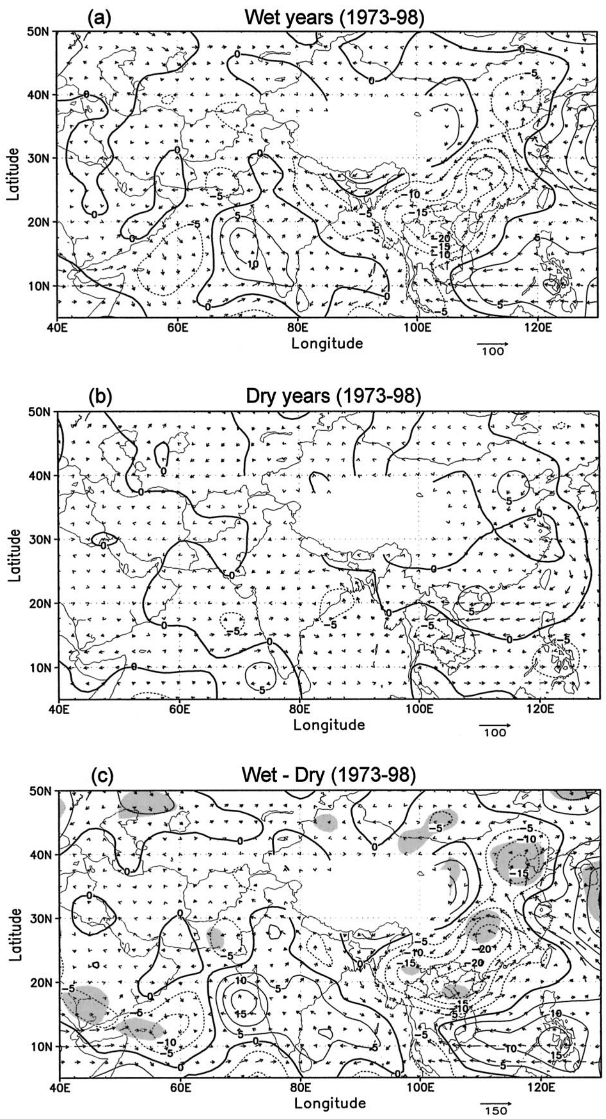

FIG. 7. Same as in Fig. 5 but for epoch 1973–98.

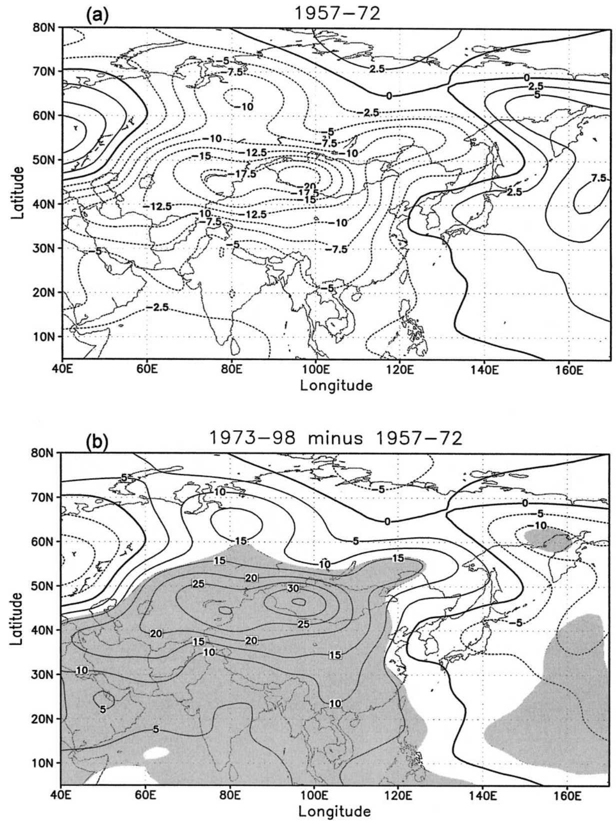

FIG. 8. Geopotential height anomalies at 500 hPa for (a) epoch 1957–72 and (b) the difference between the two epochs, 1957–72 and 1973–98. The anomalies are relative to the mean of the period 1957–98. (b) Shading indicates significant changes in geopotential height at 95% confidence level.

ics in regional circulations of the two regions and disconnected their rainfall variations as shown by the correlations in Fig. 2c. Lacking the connection between the circulation and moisture variations in the Indian monsoon region and in northern China resulted in disorganized variations of rainfall in those regions. Because of the disconnection, the Indian monsoon variations that could have resulted from ENSO, when its effect on the monsoon was strong, could not influence the summer rainfall variation in northern China. Thus, the ENSO effect on northern China rainfall was absent (Fig. 2b). These results, after compared to that from the previous epoch, indicate that the multidecadal alternation of the large-scale circulation in the Eurasian continent may have affected interactions of regional circulations in the Indian monsoon region and in northern China, and resulted in variations of their relationship. Variations in this relationship have played a critical role in the Indian summer monsoon carrying the ENSO effect onto the summer rainfall variation in northern China.

5. Summary and discussions

The results presented in the previous sections show that the summer rainfall in northern China has been affected by ENSO, and the ENSO influence has varied somewhat regularly in the last century. The ENSO effect was particularly strong in the epochs 1890–1904 and 1957–72, and marginally significant in the epoch 1927–43, and was very weak and insignificant in the two epochs 1905–26 and 1943–56 and in the recent decades after 1972. This multidecadal variation of the ENSO influence is quite different from the otherwise persistent or ‘‘accountable’’ effect of ENSO whenever an El Niño or a La Niña occurred. This difference indicates that the ENSO effect on the summer rainfall in northern China was not through the PJ teleconnection, which describes a chain of waves emanating to higher latitude from the tropical region resulting from changes of the SST during ENSO. Additional analyses further show that summer rainfall variation in northern China also is different from the variation of the East Asia summer monsoon and western North Pacific summer monsoon, both of which have been found to be closely related to the PJ pattern (Huang 2004) and with consistent variations associated with ENSO (Wang et al. 2001). These results have prompted this search of a potential role of the Indian summer monsoon in connecting as well as regulating the ENSO effect on summer rainfall in northern China.

This potential role of the Indian summer monsoon is confirmed by the results of both statistical and atmospheric circulation analyses. These results show that the Indian summer monsoon has a peculiar relationship with summer rainfall variation in northern China. A few key features of this relationship are that it has varied at a multidecadal scale in the last century, strong in some epochs and weak in others. Immediately after those changes of the relationship the ENSO effect on northern China rainfall occurred. A strong (weak) ENSO effect was observed in variations of the northern China summer rainfall in epochs when the rainfall was strongly correlated (weakly or not correlated) with the Indian monsoon rainfall. These results demonstrate the Indian summer monsoon as a means to engage ENSO with northern China rainfall variation.

Some physical processes connecting variations of summer rainfall in northern China with the Indian summer monsoon are found to be associated with variations of the large-scale circulations in the Eurasian continent. The circulation showed a lowering of the geopotential height at 500 hPa with a broad center in northern China and Mongolia in the epochs when variations of the Indian summer monsoon and the northern China rainfall were strongly correlated. This particular circulation anomaly enhanced cyclonic rotation in wind across southern and eastern China, creating a moisture convoy between northern China and the Indian monsoon region with coherent convergence/divergence in those two regions. An opposite anomaly of the circulation with rising geopotential height at 500 hPa in the opposite epochs missed the features connecting circulation and rainfall variations in the two regions. In those epochs, variation in the Indian summer monsoon resulting from ENSO failed to be carried to and affect the northern China summer rainfall. These results explain a mechanism that establishes a critical role of the Indian summer monsoon to engage summer season SST variations associated with ENSO and the northern China rainfall fluctuation.

Although this mechanism needs to be further understood in its dynamic details, such as the development of the moisture convoy and the synergic moisture convergence/divergence in northern China and the Indian monsoon region, the role described by the mechanism for the Indian monsoon to connect ENSO with the summer rainfall in northern China could be useful. When this relationship is intact the ENSO variations, whose forecasts have been improving, could be used to guide the forecasts of northern China summer rainfall anomalies and to assist planning and management of the water resources in the semiarid regions in northern China. When this relationship is inactive, however, sources/mechanisms affecting the rainfall variations still need to be understood in order to complete our understanding of the predictability of the northern China summer rainfall. Identifying these sources and mechanisms are the goals of additional studies.

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REFERENCES

Chelliah, M., 1999: Climate shift-like variations in the late 1960's and early 1970's: Is it real or is it reanalysis? *Proc. 24th Annual Climate Diagnostics and Prediction Workshop,* Tucson, AZ, U.S. Dept. of Commerce, NOAA, NWS/NCEP/CPC, 347–350.

Dai, A., I. Y. Fung, and A. D. Del Genio, 1997: Surface observed global precipitation variations during 1900–88. *J. Climate,* **10,** 2943–2962.

Ding, Y., 1994: *Monsoon over China.* Kluwer Academic, 420 pp.

——, 2003: Interdecadal variability of the temperature and precipitation patterns in the East-Asian monsoon region. *Proc. Int. Symp. on Climate Change,* Beijing, China, China National Climate Committee, 6–7.

Guo, Q., and J. Wang, 1988: Comparison analysis on China and India precipitation (in Chinese). *Trop. Meteor.,* **4,** 53–60.

Hu, Q., and S. Feng, 2001: A southward migration of centennial-scale variations of drought/flood in eastern China and the western United States. *J. Climate,* **14,** 1323–1328.

Huang, G., 2004: An index measuring the interannual variation of the East Asian summer monsoon—The EAP index. *Adv. Atmos. Sci.,* **21,** 41–52.

Huang, R., and Y. Wu, 1989: The influence of ENSO on the summer climate change in China and its mechanisms. *Adv. Atmos. Sci.,* **6,** 21–32.

——, L. Zhou, and C. Wen, 2003: The progresses of recent studies on the variabilities of the East Asian monsoon and their causes. *Adv. Atmos. Sci.,* **20,** 55–69.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kinter, J. L., III, K. Miyakoda, and S. Yang, 2002: Recent change in the connection from the Asian monsoon to ENSO. *J. Climate,* **15,** 1203–1215.

Kistler, R., and Coauthors, 2001: The NCEP–NCAR 50-Year Reanalysis: Monthly means CD-ROM and documentation. *Bull. Amer. Meteor. Soc.,* **82,** 247–267.

Krishnamurthy, V., and B. N. Goswami, 2000: Indian monsoon–ENSO relationship on interdecadal timescale. *J. Climate,* **13,** 579–595.

Kumar, K. K., B. Rajagopalan, and M. A. Cane, 1999: On the weakening relationship between the India monsoon and ENSO. *Science,* **284,** 2156–2159.

Lau, K.-M., K.-M. Kim, and S. Yang, 2000: Dynamical and boundary forcing characteristics of regional components of the Asian summer monsoon. *J. Climate,* **13,** 2461–2482.

Lau, N.-C., and M. J. Nath, 2000: Impact of ENSO on the variability of the Asian–Australian monsoons as simulated in GCM experiments. *J. Climate,* **13,** 4287–4309.

——, and ——, 2003: Atmosphere–ocean variations in the Indo-Pacific sector during ENSO episodes. *J. Climate,* **16,** 3–20.

Nitta, T., 1987: Convective activities in the tropical western Pacific and their impact on the northern hemisphere summer circulation. *J. Meteor. Soc. Japan,* **65,** 373–390.

Parthasarathy, B., A. A. Munot, and D. R. Kothwale, 1995: Monthly and seasonal rainfall series for all-India homogeneous regions and meteorological subdivisions: 1871–1994. Indian Institute of Tropical Meteorology Research Rep. RR-065, Pune, India, 113 pp.

Qian, W., and Y. Zhu, 2001: Climate change in China form 1880 to 1998 and its impact on the environmental condition. *Climatic Change,* **50,** 419–444.

Quan, X. W., H. F. Diaz, and C. B. Fu, 2003: Interdecadal change in the Asia-Africa summer monsoon and its associated changes in global atmospheric circulation. *Global Planet. Change,* **37,** 171–188.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.,* **108,** 4407, doi:10.1029/2002JD002670.

Shukla, J., and D. A. Paolino, 1983: The Southern Oscillation and long-range forecasting of the summer monsoon rainfall over India. *Mon. Wea. Rev.,* **111,** 1830–1837.

Slingo, J., 1999: The Indian summer monsoon and its variability. *Beyond El Niño: Decadal Variability in the Climate System,* A. Navarra, Ed., Springer, 103–118.

Torrence, C., and P. J. Webster, 1999: Interdecadal changes in the ENSO–monsoon system. *J. Climate,* **12,** 2679–2690.

Wang, B., and LinHo, 2002: Rainy season of the Asian–Pacific summer monsoon. *J. Climate,* **15,** 386–398.

——, R. Wu, and K.-M. Lau, 2001: Interannual variability of the Asian summer monsoon: Contrasts between the Indian and the western North Pacific–East Asian monsoons. *J. Climate,* **14,** 4073–4090.

Wang, S. W., 1994: *Introduction to Climate System.* China Meteorology Press, 250 pp.

Wilks, D. S., 1995: *Statistical Methods in Atmospheric Sciences.* Academic Press, 467 pp.

Yatagai, A., and T. Yasunari, 1995: Interannual variations of summer precipitation in the arid/semi-arid regions in China and Mongolia: Their regionality and relation to the Asian summer monsoon. *J. Meteor. Soc. Japan,* **73,** 909–923.

Ye, D.-Z., and R. H. Huang, 1996: *Study on the Regularity and Formation Reason of Drought and Flood in the Yangtze and Huaihe River Regions* (in Chinese). Shandong Science and Technology Press, 387 pp.

Zhang, J. J., and L. Ge, 1983: *Fundamentals of Medium and Long-Range Weather Prediction.* China Meteorology Press, 445 pp.

Zhang, R., A. Sumi, and M. Kimoto, 1999: A diagnostic study of the impact of El Nino on the precipitation in China. *Adv. Atmos. Sci.,* **16,** 229–241.